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AUTOMATIC GENERATION OF VIRTUAL LUMBAR MOTION SEGMENTS FOR POPULATION-BASED SIMULATION OF LUMBAR SPINE BIOMECHANICS

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INTRODUCTION

Computational modeling of the spine has become a viable option for evaluating new implants and procedures. Most models described in the literature, however, represent only a single subject and neglect the normal variation that exists among specimens. A probabilistic simulation comprised of virtual specimens representing a broad population of subjects can address this limitation and be used to evaluate implants or procedures pre-clinically. Challenges exist to applying probabilistic modeling techniques to biologic systems, and perhaps the greatest is parameterization of the anatomy to capture normal variation in shape from specimen to specimen. It's also critical to implement soft tissues in a robust, automated manner that produces representative biomechanics. The purpose of our research is to overcome these challenges and develop a probabilistic framework to perform population-based studies of lumbar spine biomechanics. This paper describes our results to date for the automated generation of virtual lumbar motion segments.

METHODS

Statistical shape modeling was used to parameterize the anatomy of an L3-L4 functional spinal unit. Geometry of eight normal lumbar specimens was extracted from CT scans (6 female, 2 male, 54±16yrs) and a quadrilateral surface mesh was applied to one arbitrarily chose L3 body. The surface mesh was then morphed to the remaining vertebral bodies using HyperMesh software (Altair, Troy, MI). Based on the findings of a previous validation study [1] nodal coordinates of the L3 and L4 bodies from each FSU were combined into a single data vector, and vectors representing each of the eight specimens formed the columns of a system data matrix. A principal component analysis (PCA) was performed on the covariance of this matrix. In PCA, eigenvalues of the covariance matrix represent the variance of shape along each of the eigenvectors, which are the principle shape modes. Each of the eight specimens could then be represented exactly by the expression,

$$P = P_{mean} + \sum_{j=1}^{m} b_j * c_j \qquad (1)$$

where P_{mean} represents the mean FSU, the b_j are scalar coefficients, and the c_j are the eigenvectors computed from the PCA. The coefficients b_j were assumed normally distributed. It was then possible to instantiate any number of unique virtual specimens by randomly sampling the normal curve for each coefficient, b_j.

Because it is known that spine biomechanics are sensitive to facet articulation [2], instantiated specimens from the SSM were compared to natural specimens reconstructed directly from CT data to confirm that the virtual specimens exhibited normal facet mechanics. This comparison was performed with a finite element model comprised of all ligaments (non-linear springs [3]), an intervertebral disc (hyperelastic annulus, fluid cavity for the nucleus), linear elastic cartilage (2 mm thick), and a facet joint gap of 0.5 mm (Figure 1).

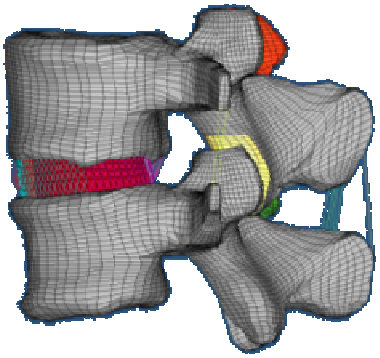

Figure 1: L3-L4 motion segment with ligaments, intervertebral disc, and cartilage.

Soft tissue constitutive behavior and FSU range of motion were validated against previously reported experimental data [4]. For the comparison between instantiated and natural specimens, facet contact was evaluated subject to a 7.5 Nm right axial torque with an 800 N follower load [4]. All models were solved with Abaqus/Explicit (SIMULIA, Providence, RI).

For the purpose of probabilistic analysis, it is almost always desired to perform tens or hundreds of trials with the deterministic model of interest. To facilitate this process with the L3-L4 FE model driven by the SSM, a procedure was developed to automatically generate a large number of virtual specimens, each with distinct anatomical shape. The SSM produces virtual specimens with identical topology (node numbers and locations relative to anatomical features are consistent) so the ligaments were automatically placed to connect specific regions of the mesh. Alignment of adjacent vertebral bodies was initially performed manually based on natural disc spacing, adequate overlap of superior and inferior facet surfaces, and natural lordosis. Intervertebral discs were scaled appropriately to fit each instantiated motion segment. Bone geometry was modeled with rigid surfaces, but facet cartilage was treated using deformable solid meshes bonded to the bone. Therefore, a process was developed to automate cartilage creation for each facet joint.

Cartilage surface nodes and elements from instantiated specimens were extracted. From these node coordinates local element normals were calculated using the cross product of the element diagonal vectors. Element normals were then averaged. Three layers of subsurface nodes were aligned into the facet bone along the surface normal for 2 mm. Subsurface node alignment was performed by first finding the unit vector of the averaged surface normal. Then for each node, equation 2 was used.

$$SN_{coord} = N_{coord} - d*unit \qquad (2)$$

SN_{coord} is the node coordinate for each layer of subsurface node, N_{coord} is the coordinates of the surface node, and d is the distance between layers which varies, depending on layer, from 0 to 2 mm by 0.6666 mm.

RESULTS

Motion segments instantiated from the SSM demonstrated noticeable shape variation; however the facet joints mated qualitatively similar to natural specimens (Figure 3).

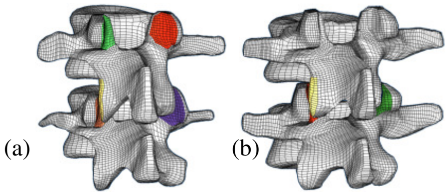

Figure 3: Instantiated motion segments (b) and naturals (a) were constructed for preliminary FE evaluation of facet contact

Quality of facet joint mating was evaluated quantitatively with the FE model subjected to right axial rotation. Contact pressure and area produced similar results to the natural models showing that instantiated motion segments were biomechanically viable and they were similar to natural specimens [1].

Automation of facet cartilage produced cartilage geometry that was flush with the facet bone geometry and protruded into the bone as illustrated in Figure 4.

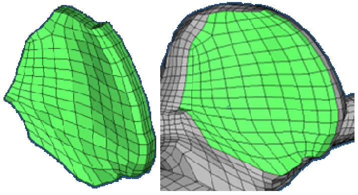

Figure 4: (left) automated cartilage with hexahedral elements (right) automated cartilage positioned in facet joint for contact

Three layers of deformable hexahedral elements were created with little to no element distortion. The auto cartilage FE model was qualitatively compared to the manually created model for the natural specimen described above and similar visual results were obtained. Contact pressure and area were quantitatively compared between FE models with manual cartilage vs automated cartilage to validate the automation process. Contact area was observed in the same approximate facet location and contact pressure was similar: 2.22 MPa for the automated cartilage compared to 2.43 MPa for the manual specimen.

DISCUSSION

Morphologic variation in the lumbar spine was characterized using a statistical shape model. Instantiated motion segments had similar facet articulation as natural specimens. Cartilage generation that was automated for a probabilistic study resulted in quality hexahedral meshes that fit flush into the facet geometry.

With the success of instantiating geometry for a motion segment, the same principles can be applied to the entire lumbar spine. Next steps for creating a probabilistic model are to automate the alignment of adjacent segments, intervertebral disc positioning, and implementation of the probabilistic computations. Preliminary probabilistic analysis will be performed based on the Monte Carlo method similar to previous studies in our lab [**5**].

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[1] Huls et al., Abstract 56th annual meeting, ORS, 2009. [2] Holzapfel et al., Eur Spine J 15:849-856, 2006.[3] Chazel et al., J.Biomech 18:167-176, 1985. [4] Rohlmann et al., J.Biomech 39:2484-2490, 2006. [5] Petrella et al, Clin Orthop Relat Res 467: 50-55, 2009.